GaAs-based near-infrared up-conversion device fabricated by wafer fusion

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Reported for the first time is a full GaAs-based room-temperature near-infrared (NIR) up-conversion device fabricated by wafer-fusing a GaNAsSb/GaAs *pin* photodetector (PD) with a GaAs/AlGaAs light-emitting diode (LED). NIR photons with wavelengths in the range 1.3–1.6 μm were up-converted to 0.87 μm.

Introduction: Infrared up-conversion devices have attracted much interest owing to various applications such as lasing [1], three-dimensional displays [2], laser cooling [3], and infrared imaging [4]. Compared with other up-conversion techniques, photodetector (PD) light-emitting-diode (LED) up-conversion has the advantages of compactness, simplicity, low excitation power and high operation temperature. A PD-LED up-conversion device is typically composed of two major parts, a PD and an LED. Incident infrared photons are absorbed by the PD, resulting in a photocurrent that drives the LED to emit photons with higher energy. The most investigated NIR PD is the InGaAs photodiode based on an InP substrate, which can routinely reach a responsivity higher than 1 A/W. Since 2000, NIR up-conversion devices with InGaAs/InP PDs have been fabricated [5, 6]. In addition to InP-based PDs, GaAs-based NIR PDs lattice matched to GaAs substrate are now able to cover the important 1.3–1.55 μm wavelength region, with responsivities comparable to InGaAs/InP photodiodes [7, 8]. On the light emitting side, high efficiency is desired. InP-based LEDs have very low internal quantum efficiencies of less than 1%. However, GaAs/AlGaAs LEDs are capable of high internal efficiencies of near 100% [6]. Therefore, NIR up-conversion devices with both PD and LED based on GaAs substrates are advantageous.

In an earlier study, we demonstrated GaAs-based NIR up-converters with the potential of reaching high up-conversion efficiencies [9]. However, the sample was composed of two discrete parts, a GaAs-based PD and a commercial LED, while in the present work we have successfully fabricated an integrated full GaAs-based NIR up-conversion device for the first time.

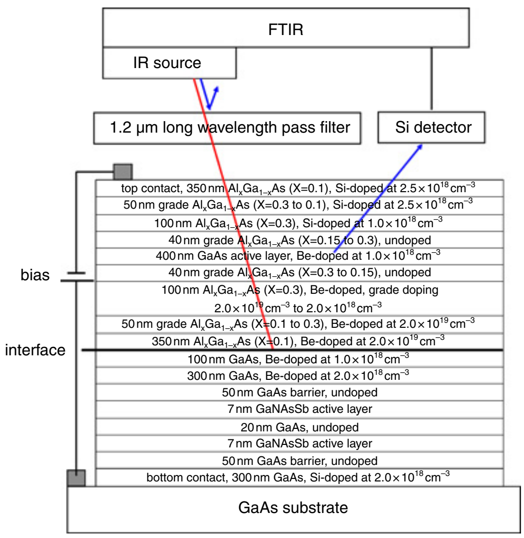

Fig. 1 *Schematic of sample structure and experimental setup for demonstrating up-conversion*

Device design and fabrication: The NIR up-converter device is fabricated by wafer-fusing a GaNAsSb/GaAs PD and a GaAs/AlGaAs LED, both grown by molecular-beam epitaxy on GaAs substrates. The PD is a *pin* structure, with a $GaN_{0.025}As_{0.615}Sb_{0.36}$ double quantum well active region designed for absorption near 1.55 μm. More sample details were given in [7], where both annealed and as-deposited GaNAsSb/GaAs detector characteristics were studied. To have broad response, an as-deposited sample is used in this study. The LED efficiency is crucial to the up-converter performance, and Ban *et al.* [6] have optimised GaAs/AlGaAs LEDs for infrared up-conversion application. The LED used in this study was the optimised LED design of [6].

The two epitaxial surfaces were then bonded together via wafer fusion. Afterwards, the substrate of the LED was chemically removed, and square mesa devices were fabricated. The detailed structure of the device and the experimental setup are schematically shown in Fig. 1. During measurement, the device was biased so that the LED is positively biased and the PD negatively biased. All measurements are done at room temperature.

Results and discussion: We first investigated the PD responsivity of the up-converter. The bias dependent responsivity of a typical 400 × 400 μm mesa device illuminated by a 1.3 μm laser diode is given in Fig. 2 (solid curve). It increases nearly linearly with bias at first, and arrives at a relatively flat region of around 0.02 A/W, and then increases rapidly to a value of about 0.16 A/W (15.3% quantum efficiency) at 7 V, showing no trend of saturation. This behaviour is consistent with our previous report on the GaNAsSb/GaAs PD [7], confirming that wafer fusion preserved the original properties of the fused structure.

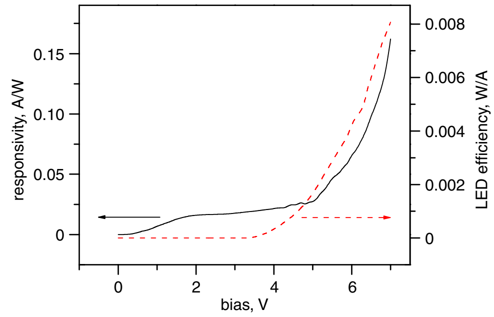

Fig. 2 *Bias dependent room-temperature PD responsivity (solid curve) under 1.3 μm illumination and external LED light emitting efficiency (dashed curve)*

We then measured the LED efficiency of the up-converter. The electroluminescence spectrum collected with a Fourier transform infrared spectrometer (FTIR) exhibits an emission peak at 870 nm, agreeing with the GaAs bandgap. The dashed curve in Fig. 2 shows the LED external efficiency as a function of bias. The efficiency is negligible for low bias voltages, but turns on at 4 V, and exceeds 8.0×10^{-3} W/A at 7 V bias (about 10 mA current). Assuming a 2% escape probability of the photons from the LED with a simple planar geometry, the internal quantum efficiency of an LED is calculated to be 40%. In comparison, the separate LED before wafer fusion has an efficiency of 7.5×10^{-3} W/A at the same injection current, showing that the wafer fusion technique has little influence on the LED performance. The small difference is with our measurement error and device-to-device variation.

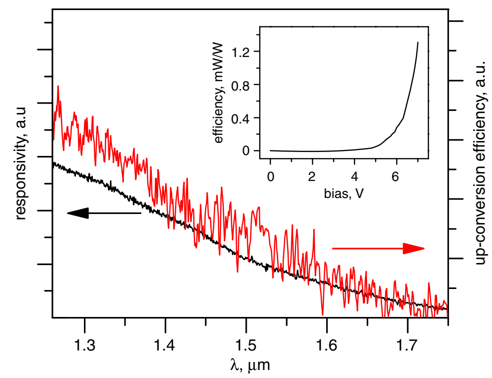

Fig. 3 *Room-temperature spectral response (lower curve) and up-conversion spectrum (upper curve) of up-converter*

Inset: bias dependent room-temperature up-conversion efficiency under 1.3 μm laser illumination

We have shown that both PD and LED structures work properly after wafer fusion. The intended function of the device, to convert NIR photons to higher frequency, is then tested. As shown in Fig. 1, the infrared radiation from the FTIR internal infrared light source is filtered by a 1.2 μm long-pass filter, and then absorbed by the GaNAsSb active layer, inducing a photocurrent to drive the GaAs/AlGaAs LED structure to emit photons with shorter wavelength. The upper curve in Fig. 3 shows the up-conversion spectrum normalised to the background. The up-conversion spectrum agrees with the spectral response, the lower curve in Fig. 3. The inset of Fig. 3 shows the bias dependent up-conversion efficiency. At low bias voltages, the up-conversion efficiency is nearly zero. The voltage turn-on bias is mainly determined by the LED. At 7 V bias, an up-conversion efficiency of 1.3 mW/W is observed, and it rises rapidly with increasing bias. As a concept demonstration, the GaNAsSb absorption layer of the studied sample is thin (in total 14 nm), so the up-conversion efficiency is not optimum. However, the 1.3 mW/W value already represents a 6.1% internal up-conversion quantum efficiency at 1.3 μm. The efficiency can be improved by using a thicker GaNAsSb absorption layer.

To achieve higher up-conversion efficiency, higher device bias is desired. However, this results in an increase in dark current and dark current noise. As a result, higher bias might actually lead to a lower signal-to-noise ratio. For this device, the ratio of emission power up-converted from per unit power incident light (say, 1 mW at 1.3 μm) to that resulting from dark current is 0.11 at 5 V bias, and 0.016 at 7 V bias.

Conclusion: We have fabricated an integrated full GaAs-based NIR up-conversion device via wafer fusion. The use of wafer fusion demonstrates the feasibility of the concept, and a full expitaxial growth approach will be investigated.

Acknowledgments: This work was supported in part by the Natural Science Foundation of China (10734020), National Major Basic Research Project (2010CB933702), and Shanghai Municipal Major Basic Research Project (09DJ1400102).

9 December 2010
doi: 10.1049/el.2010.3543
One or more of the Figures in this Letter are available in colour online.

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